

Federal Transit Administration 27th Annual Engineer's Week



Transit Tunnel Design and Construction Considerations

June 2, 2011

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Topics

- Types of Tunnels
- Design Considerations
- Subsurface Conditions
- Construction Methods
- Risk Management
- Contract Delivery Methods



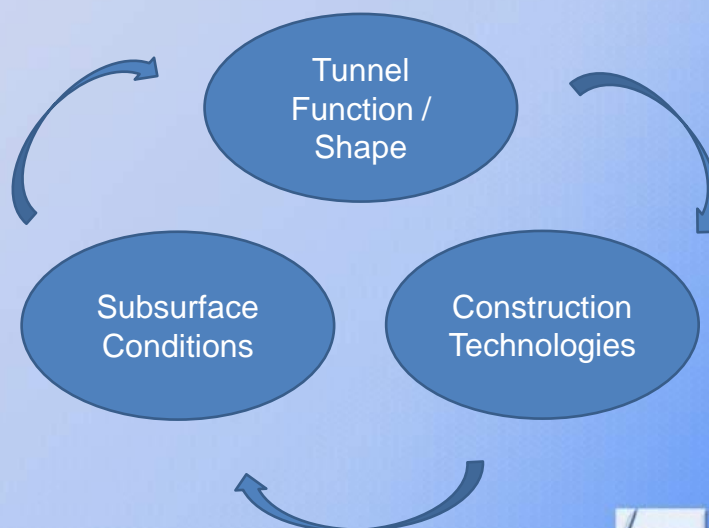
Tunnel Types

- As defined by function
 - Running tunnel – single or dual track
 - Station – binocular, cavern, or stacked
 - Cross over
 - Cross passage
- Shape
 - Based on function and ground conditions



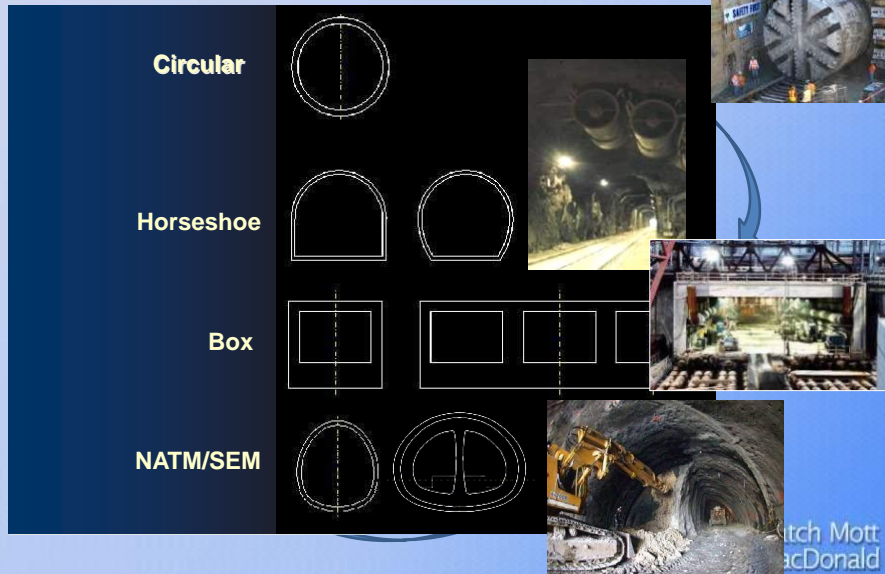
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Tunnel Function and Shape



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Tunnel Function and Shape



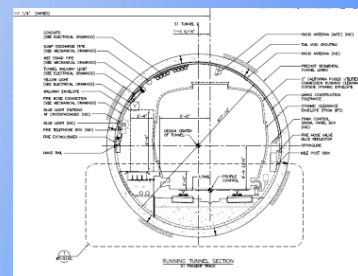
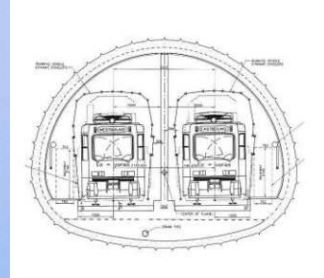
Design Considerations

- Horizontal curves
 - Curvature vs design speed
 - Dynamic envelope
- Vertical curves / grades
 - Heavy rail – 2 to 2.5%
 - Light rail – 6%
- Alignment depth
 - Hydrostatic pressure
 - Buoyancy (uplift)



Cross Section Clearance

- Rail bed, track ties, top of rail
- Dynamic envelope (function of speed and curve radius)
- Emergency walkway
- Catenary (LRT)
- Circular (single track)
- Compound (dual track)



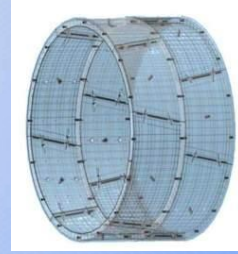
Complex Transitions

- East Side Access
- Tunnel Wye's to accommodate bifurcations



Lining Design

- Lining principles
 - Ground/structure interaction
 - The ground supports the lining and vice versa
- Long-term loads
 - Ground
 - Groundwater
- Short term loads
 - Handling (casting, erection)
 - Machine thrust



Tunnel Systems

- **Ventilation**
- Drainage
- Traction Power
- Fire suppression
- Emergency egress
- Signaling



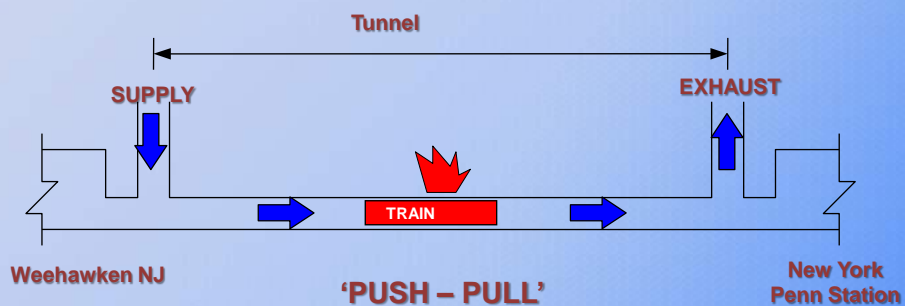
Ventilation Design

- Longitudinal (push/pull)
- Transverse
- Semi-transverse
- Uni-directional traffic
- Bi-directional traffic



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Rail Tunnel Ventilation



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Subsurface Conditions

- **Hard Rock**
 - Sedimentary (sandstones)
 - Igneous (granites, basalts)
 - Metamorphic (schists, gneiss)
- **Soft Rock**
 - shales, claystones, siltstones
- **Discontinuities**
 - Joints, shears, faults, contacts



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Subsurface Conditions

- **Soils**
 - sands, silts, clays
 - Gravels, cobbles, boulders
- **Mixed Face Ground**
 - Dissimilar rock strengths
 - Rocks and soils
 - Sands overlying clays
- **Hydrology**
 - Above the water table
 - Below the water table
 - Subaqueous



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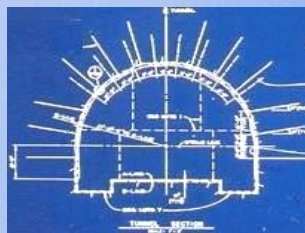
Tunneling Methods

	Rock	Soft Ground
➤ <i>Drill and blast tunneling</i>	✓	
➤ <i>TBMs/Roadheaders</i>	✓	
➤ <i>Sequential excavation</i>	✓	✓
➤ <i>Shields/Pressurized face</i>	✓	✓
➤ <i>Precast concrete linings</i>	✓	✓
➤ <i>Jacked box tunnels</i>		✓



Hard Rock – Drill and Blast

- Objective – remove the rock with minimum of blast damage
 - More holes, low charge weight / delay
 - Smooth wall blasting methods
- Excavation Sequencing
 - Small diameter – full face “rounds”
 - Larger diameter – sequential excavation



Hard Rock - Drill and Blast



H-Series Atlas Copco Rocket Boomer

Unigel Cartridges



Trim Tex air-cushioned cartridges

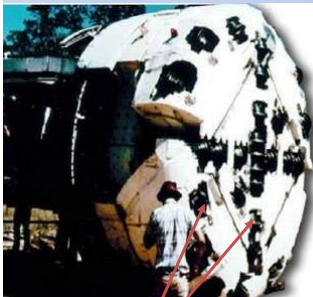


Nonel Primadet blasting caps

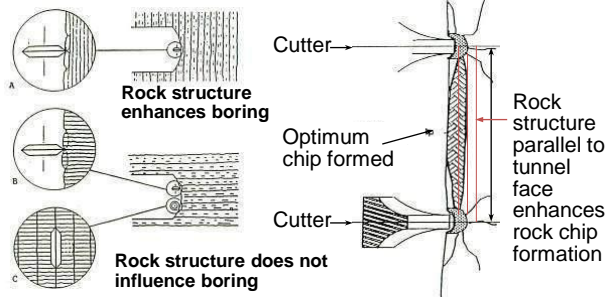


Hard Rock - TBMs

- ◆ Rotating cutter head
- ◆ Discs mounted on cutter head
- ◆ Forward propulsion system
- ◆ Mechanical muck removal
- ◆ Forward propulsion system
- ◆ Ground support equipment



TBM disc cutters



Roadheaders

- ◆ Rotating cutter head(s)
- ◆ Articulating boom
- ◆ Mechanical mucking
- ◆ Variable shape openings



Sequential Excavation Method

- Sequential Excavation Method
- aka **N**ew **A**ustrian **T**unneling **M**ethod (NATM)
- (engineered by a New Austrian...)
- aka **N**orth **A**merican **T**unneling **M**ethod
- aka **N**ot **A**nyone's **T**unneling **M**ethod

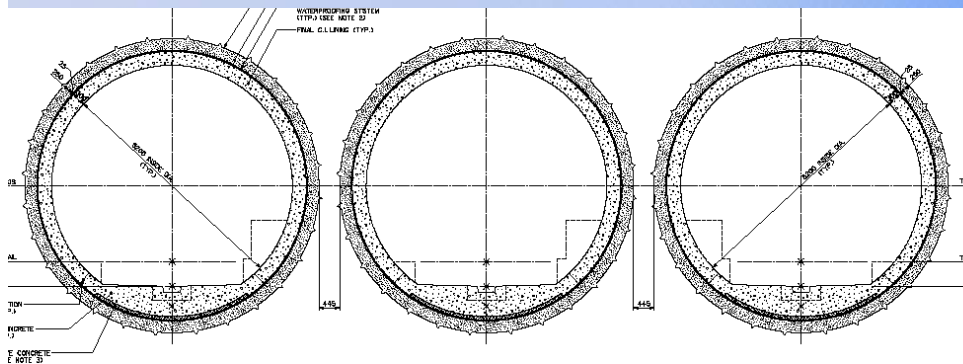
SEM Examples

Mission Valley East LRT
San Diego State University

SEM Examples

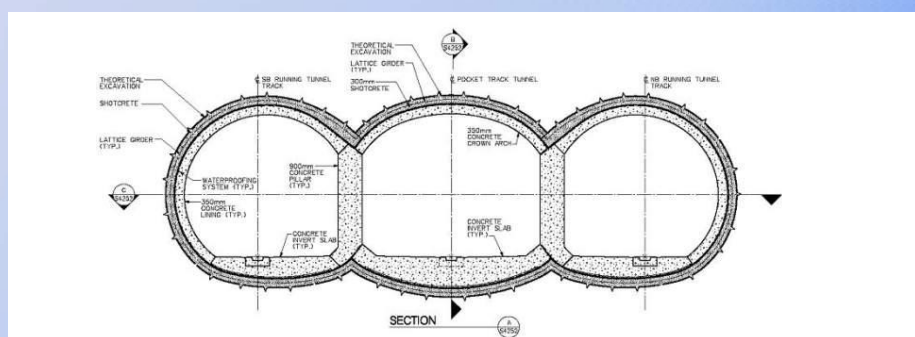
Beacon Hill Tunnel and Station

SEM Example: Toronto's Spadina Subway Extension Triple Tunnels with Narrow Pillar



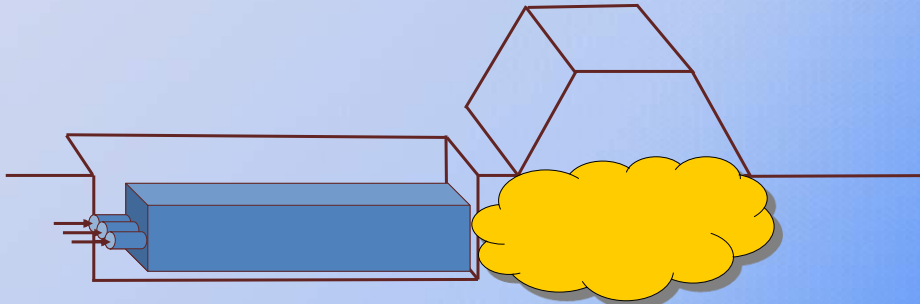
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Completed Structure



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Box Jacking Principles



- Stabilize the ground (grouting or freezing)
- Excavate jacking pit on one side of crossing
- Cast structure within jacking pit
- Position Jacking Rams
- Apply jacking force
- Excavate ground, extend rams, and jack box forward



Box Jacking – Central Artery



Table 1. Key Tunnel Dimensions

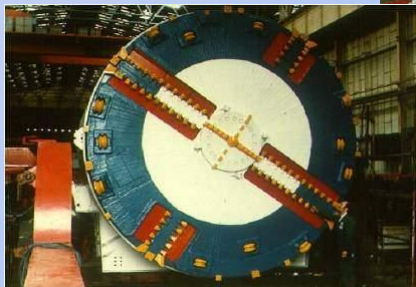
Tunnel	Width (ft)	Height (ft)	Length (ft)	Weight (tons)	Max. Design Jacking Loads	
					At RJS (tons)	At IJS (tons)
Ramp D	78	38	167	17,000	12,600	14,000
I-90 WB	78	38	258	27,000	12,000	16,500
I-90 EB	79	35.5	359	31,000	12,800	18,000

RJS = rear jacking station; IJS = intermediate jacking station.



Soft Ground Tunneling

- Open face shields
- Closed face machines
- Pressurized face machines



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Open Face / Closed Face

- Open face
 - Shields
 - machines

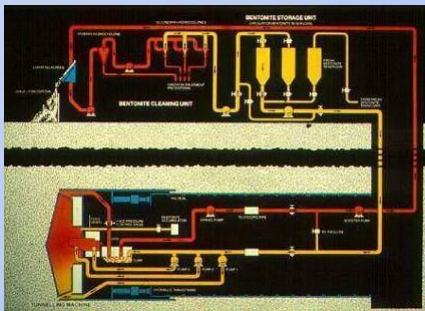
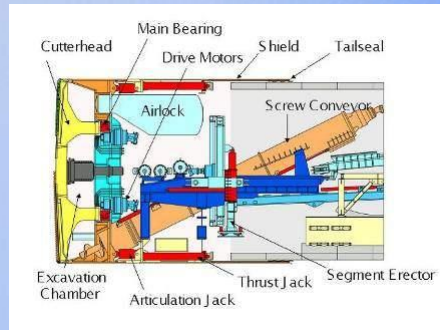


- Closed face
(cutter wheels)



Pressurized Face: EPB vs Slurry

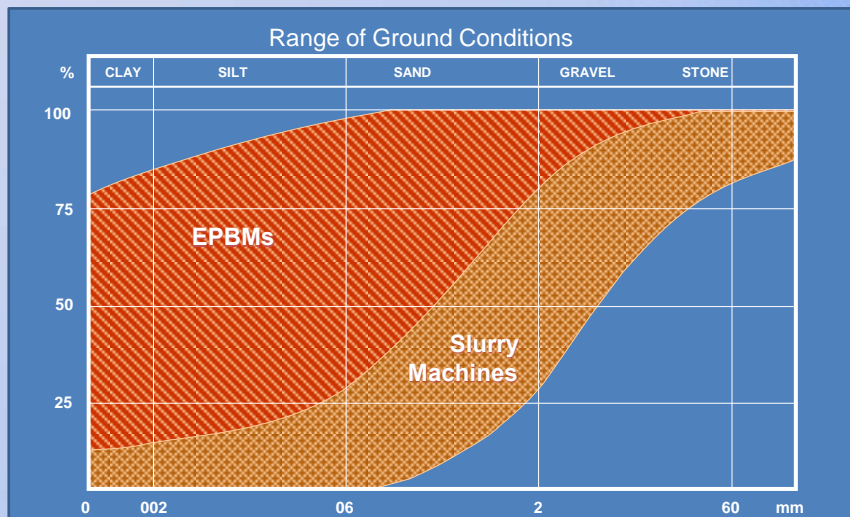
- Earth pressure balance machine (EPBM)



- Slurry pressure machine

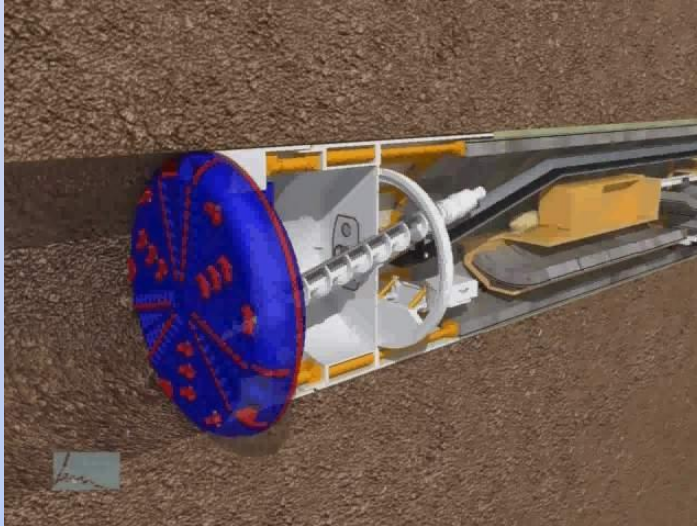
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Soil Grading Curves



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EPB Fundamentals



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EPBM - Additives

➤ Objective

- Thicken sands
- Reduce friction and abrasion
- Increase homogeneity
- Reduce stickiness
- Reduce power demand

➤ Materials

- Bentonite. 3% - 5% mix
- Long Chain Polymers. 0.1% - 0.5% mix
- Foam. 3% - 10% mix



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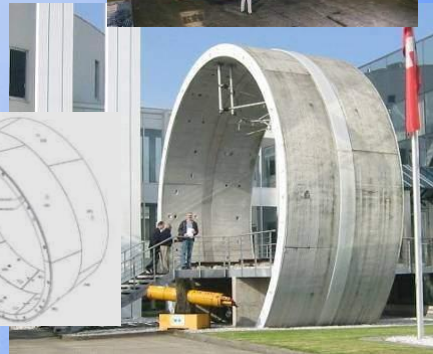
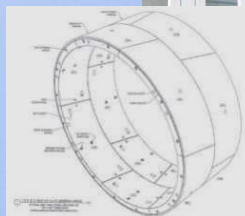
Conditioned Soil



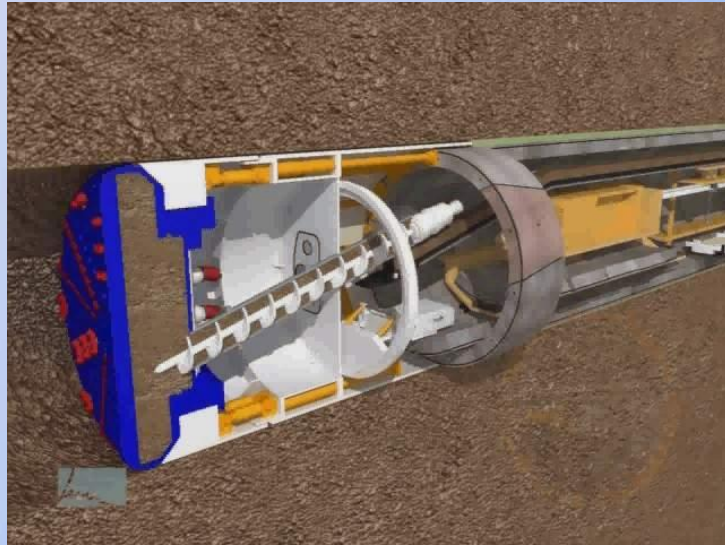
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Precast Concrete Lining

- Precast concrete segments
 - gasketed
 - Bolted
- Segment erector

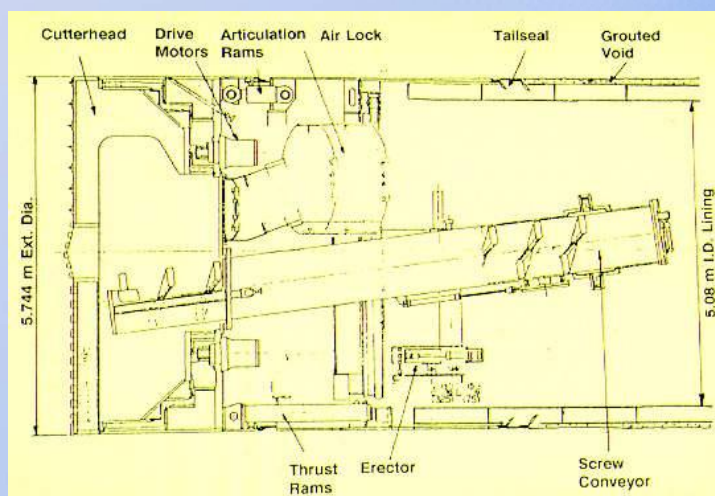


Assembly of Precast Concrete Ring



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Anacostia, Washington, DC EPBM



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St. Clair River Tunnel EPBM



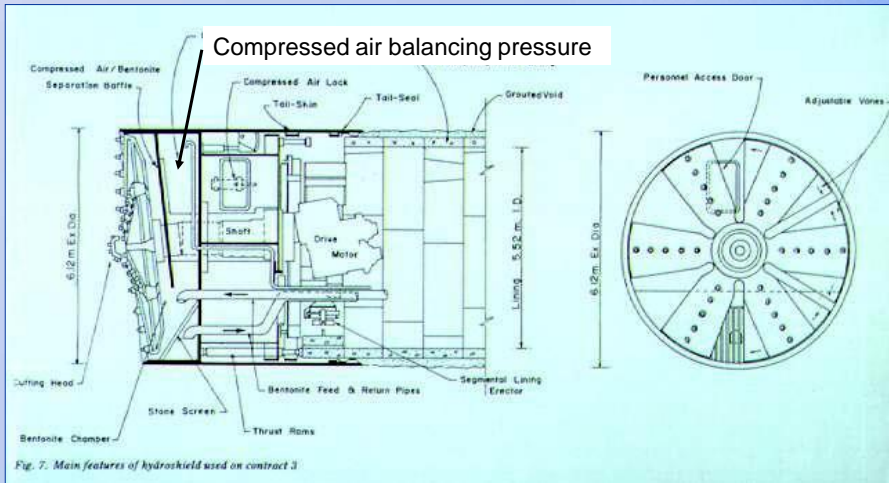
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Toronto Sheppard Subway EPBMs



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Hydroshield or Mixshield



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Hochtief Hydroshield



SMART Tunnel - Kuala Lumpur



Cross Passages

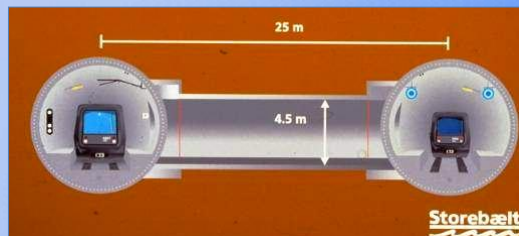
➤ Criteria / Requirements

➤ Spacings

- Typically 700 to 1,000 feet
- Emergency egress during fire events
- Adjust locations to suit ground conditions

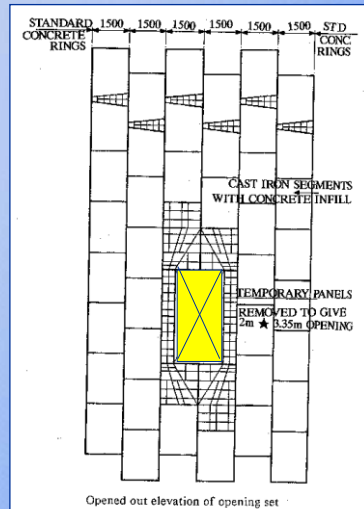
➤ Construction

- Facilitate break-out from mined tunnels
- Prevent ground loss and settlement



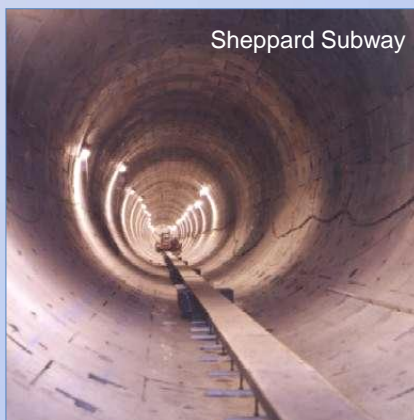
Cross Passages

- Construction Methods
 - Special Composite Segments
 - Cast iron with concrete infill
 - No taper
 - 9 in thick
 - Standard 4.5 to 5 ft wide segments
 - Remove temporary panels to provide 6.5 x 11 ft opening



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Cross Passages, Sheppard Subway



Sheppard Subway

Construction Methods



Removable panels built into segment ring

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Cross Passages, Sheppard Subway



Initial 3-ft diameter opening



Widened into full-height cross-passage

Construction Methods



Cross Passages, Sheppard Subway



Completed cross-passage construction



Risk Management

- Geologic Uncertainty
- Risk Registers



8 Tunneling “Facts of Life”

Tunnel projects are linear and can extend for miles

Subsurface conditions can vary significantly along the alignment

Subsurface conditions influence means, methods, and construction cost

Underground “surprises” = commercial risk

Contractors do not *accept* risk, they *price* risk

It's better to anticipate a risk event than be surprised

Owners want the lowest cost of construction for their projects

Contracts that anticipate risks will result in lower cost and fewer claims

Prepare a Geotechnical Baseline Report to

- Describe anticipated subsurface conditions
- Describe how those conditions will influence construction
- Describe how those conditions have influenced the design
- Identify key risks on the project
- Describe who carries the risks for conditions inside and beyond the “baselines”
- Avoid protracted legal battles



What is a Geotechnical Baseline Report

- A Contract Document
- A set of contractual assumptions – not necessarily geotechnical “fact”
- A guidance document for bidding the project
- A tool to help manage risks during construction
- A means for administering the Differing Site Conditions clause under the Contract



How a GBR Works to Reduce Claims

- Baselines identify and allocate risk
- Baselines should be a reasonable extension of the available information
- Assume the baseline is a “line in the sand”

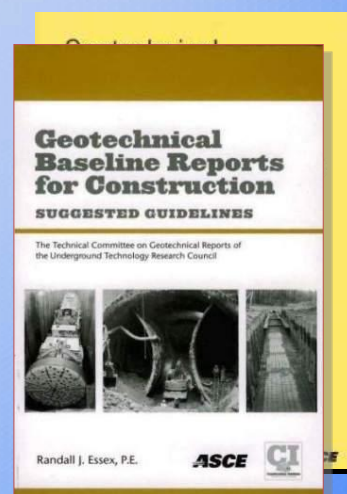


- Can set provisional sums for potential conditions outside the baselines
- Owner pays the provisional sums ONLY IF adverse conditions are encountered



ASCE Guidelines Publications

- First Published in 1997
- Updated Edition in 2007
- Reflects
 - 30 years of practice
 - Several industry feedback forums
 - The industry's views on GBR preparation and use



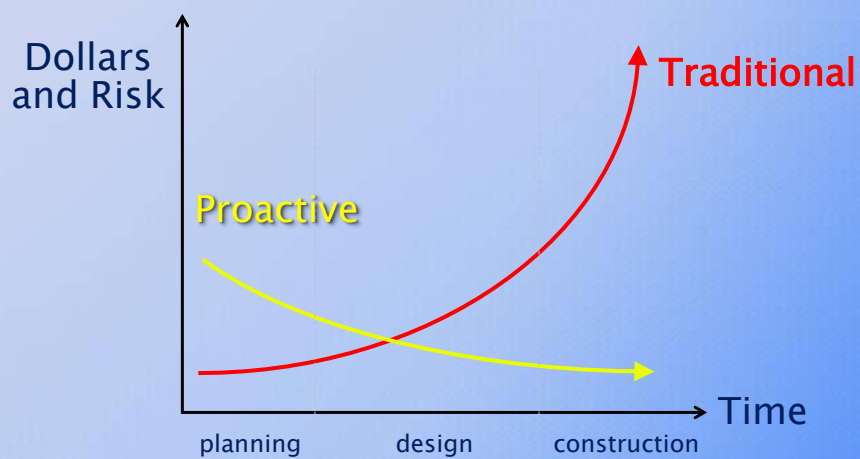
What We Mean by Risk

. . . the combination of the probability and impact of an occurrence or circumstance that may adversely affect the successful completion of your project. . .



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It Pays to be Proactive...



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Types of Risks

- Regulatory/Permitting
- Design/Operational
- Financial/Commercial/Contractual
- Site Access/Logistics
- Construction
- Environmental
- Health/Safety/Security



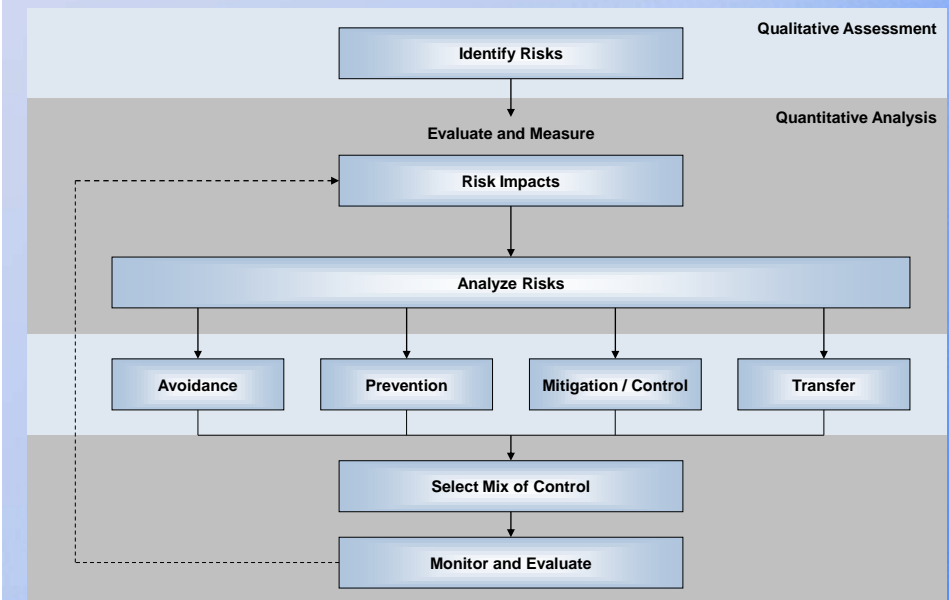
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We Recommend a Collaborative Approach to Managing Risk



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Qualitative and Quantitative Assessments



Identify, Evaluate, and Quantify

Probability	Consequence					
	0	1	2	3	4	5
6	Yellow	Red	Red	Red	Red	Red
5	Yellow	Yellow	Red	Red	Red	Red
4	Yellow	Yellow	Yellow	Red	Red	Red
3	Green	Yellow	Yellow	Yellow	Red	Red
2	Green	Green	Yellow	Yellow	Yellow	Red
1	Green	Green	Green	Yellow	Yellow	Yellow

The table is color-coded to indicate risk levels: Green for Low, Yellow for Medium, and Red for High. The words 'Low', 'Medium', and 'High' are written diagonally across the grid. A small logo 'Mott hald' is visible in the bottom right corner of the table area.

Results Summarized in a Risk Register

Severity Categories

Score	Health & Safety Risks	Commercial Risks	Operational Risks
0	No Impact	No Impact	No Impact
1	Reportable injury to Worker Multiple non-reportable injuries to workers Minor injuries to the public Potential for worker fatality Multiple injuries to the public	Extra cost - including cost of avoiding delays (£10k) Public relations embarrassment	Minor revenue losses (e.g. retail, advertising, etc.) Public relations embarrassment In-availability of roads
2	Delay in project incurring a time penalty of several weeks (affects critical path) Significant costs required to get project back on schedule (£1.5M)	Moderate extra cost - including cost of avoiding delays (£100ks)	Re-routing access roads to airport facilities Minor security alert at airport Significant revenue losses (e.g. retail, advertising, etc.)
3	Delay in project of several months incurred Major restructuring of project required Major redesign involving major costs (£2.5M)	Delay in project incurring a time penalty of several weeks (affects critical path) Significant costs required to get project back on schedule (£1.5M)	Minor effects resulting in facility closure (e.g. car park, railway) Major public security alert at airport
4	Potential to close down project	Delay in project of several months incurred Major restructuring of project required Major redesign involving major costs (£2.5M)	Major effects to airport/railway infrastructure/buildings Minor effects resulting in the closure of a runway for at least 24 hours
5			Major surface effects to airport runways

Risk Level Action

Risk Level	Action
Low	Check that no further risks can be identified Proceed with design
Medium	Consider alternative design or construction method If alternatives are not available, specify precautions to be taken List residual hazards in risk register
High	Seek alternative solutions If alternatives are not available, specify precautions to be added and Initiate specialist management strategy Planning Supervisor (where applicable)

Safety Scrutiny Levels

Likelihood Score	Severity Score					
	0	1	2	3	4	5
6	Low	Low	Low	Low	Low	Low
5	Low	Low	Low	Low	Low	Low
4	Low	Low	Low	Low	Low	Low
3	Low	Low	Low	Low	Low	Low
2	Low	Low	Low	Low	Low	Low
1	Low	Low	Low	Low	Low	Low

Risk Level Action

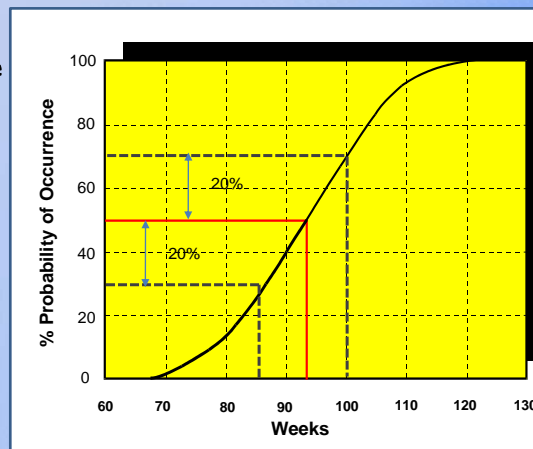
Section of the works	Feature	Risk No.	Hazard	Cause	Requirements/Constraints	Provision
Airside Road Tunnel	Ground Treatment	A.02.01	Disruption to Airport Operations	Airside surface access for ground treatment plant	May be required to mitigate risks associated with potential low cover to clay/gravel interfaces	Undertake work during Operational night time period

Callouts:

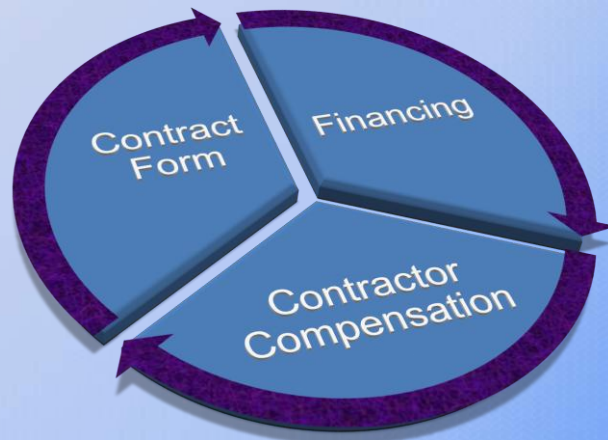
- Design Alignments, Configurations
- Construction Technologies
- Qualified Contractor(s)
- Risk Management Provisions

Monte Carlo @Risk Analysis

- Project Schedule Example
 - 93 weeks – most likely
 - 87 weeks – shortest credible
 - 100 weeks – longest credible
 - 90% envelope: 108 weeks



Contract Delivery Methods



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Contract Delivery Methods

Contractor Compensation

- Fixed Price - Lump sum with schedule of values
- Fixed Price – Unit Prices with upset limit
- Cost Reimbursable / fixed fee
- Target Cost / incentive fee

Contract Form

- Design-Bid-Build
- Design-Build
- Early Contractor Involvement
- CM At Risk

Financing

- Public Funds
- Public/Private Combinations
- Fully Private Funds

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Summary

- Tunnels are different
- Respect function and shape
- Use the right technologies
- The earlier the contractor's involvement, the better
- Pay the contractor fairly for the work performed
- Keep the lawyers out of our business



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Questions

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